Report Summarizing Criteria Pollutant Emissions Testing of 2022 Ford Escape Plug-in Hybrid Electric Flex Fuel Vehicle (PHEFFV)

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Final Report

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1 Introduction

For this program, gaseous and particulate emissions were measured from a light-duty vehicle when operated with an E10 California Reformulated Gasoline and two splash blends of E30 and E83 fuels over triplicate FTP and US06 cycles. Measurements included regulated emissions, fuel economy, PM mass, and emissions of benzene, toluene, ethylbenzene, xylene isomers, 1,3-butadiene, ethanol, and carbonyl compounds.

2 Experimental Procedures

2.1 Test Fuels

Three different fuels were used in this study. The baseline summer-grade E10 fuel (ethanol 10% by volume) was a California Reformulated Gasoline. The summer-grade E10 fuel was sourced from four (4) different refineries that were selected by CARB. Three refineries were in the South Coast Air Basin (SCAB) and one refinery was in the Northern California (Bay Area). The SCAB refineries included PBF Energy (Los Angeles), Phillips 66 (Los Angeles), and Marathon (Wilmington). The Bay Area refinery was Chevron (Richmond). The E10 fuels from all four refineries were collected by C3 Fuels. The E10 fuels were blended together in four equal parts by C3 Fuels to create the final E10 fuel.

The E30 and E83 fuels were created by splash blending denatured ASTM D4806 fuel grade ethanol with the final E10 fuel. Blending took place at C3 Fuels facility. Denatured ethanol (E98) was supplied in-kind by the ethanol industry. Table 2-1 lists the fuel properties and test methods for E10, E30, and E83 fuels.

Table 2-1. Averaged Main Physicochemical Properties of E10 and E15

Property	Test Method	Unit	E10	E30	E83
RVP (EPA Equation)	D5191	psi	7.43	7.01	4.98
DVPE (ASTM Equation)		psi	7.30	6.88	4.83
CARVP (California Equation)		psi	7.19		
Research Octane Number	D2699Mdp	ON	91.13	99.7	107.6
Motor Octane Number	D2700Mdp	ON	83.53	88	89.8
API Gravity	D4052		59.15	56.20	48.78
Specific Gravity			0.74	0.7538	0.7849
Density at 15C		g/ml	0.74	0.7536	0.7847
Heat of Combustion, Gross	D4809	BTU/lb	19264.33		
		MJ/kg	44.81		
		cal/g	10702.50		
Heat of Combustion, Net		BTU/lb	17982.00		
		MJ/kg	41.83		
		cal/g	9990.30		

Methanol	D4815	Vol%	<0.2	0.17	0.05
Ethanol		Vol%	9.66	29.95	82.60
Isopropanol		Vol%	<0.2		
tert-Butanol		Vol%	<0.2		
n-Propanol		Vol%	<0.2		
Methyl tert-butyl ether		Vol%	<0.2		
sec-Butanol		Vol%	<0.2		
Diisopropylether		Vol%	<0.2		
Isobutanol		Vol%	<0.2		
Ethyl tert-butylether		Vol%	<0.2		
tert-Pentanol		Vol%	<0.2		
n-Butanol		Vol%	<0.2		
tert-amyl methyl ether		Vol%	<0.2		
Total Oxygen		Wt%	3.59	11.12	
Carbon	D5291 CH	wt%	82.80	75.1	56.74
Hydrogen		wt%	14.05	13.58	13.14
Sulfur	D5453	ppm	6.25	3.66	1.27
Benzene	D5580	Vol%	0.60	0.47	
Toluene		Vol%	4.04	3.13	
Ethylbenzene		Vol%	0.94	0.81	
p,m-Xylene		Vol%	3.85	3.07	
o-Xylene		Vol%	1.36	1.07	
C9 plus Aromatics		Vol%	8.74	6.9	
Total Aromatics		Vol%	19.53	15.46	
Olefin	D6550	Mass %	5.03	4.36	
Distillation	D86				
IBP		deg F	101.63	108.8	133.6
5%		degF	129.53	135.2	161.0
10%		degF	135.33	141.4	165.4
15%		degF	139.07	145.5	167.7
20%		degF	142.70	149.4	169.2
30%		degF	149.20	155.6	170.8
40%		degF	157.27	160.3	171.7
50%		degF	204.50	163.8	172.1
60%		degF	228.07	166.5	172.4
70%		degF	248.70	169.2	172.7
80%		degF	275.20	255.8	173.0
90%		degF	313.63	302.0	173.4
95%		degF	342.07	333.6	174.1
Final Boiling Point		degF	394.07	388.9	-1.0
Recovered		mL	99.07	98.7	97.8

Residue		mL	0.70	0.8	1.0
Loss		mL	0.23	0.5	1.2
Particulate Matter Index			1.15	1.09	

2.2 Test Vehicle

The test vehicle used for the emissions testing was provided to UCR’s CE-CERT by RFA. The vehicle was a 2022 model year Ford Escape SEL plug-in hybrid equipped with a naturally aspirated sequential multi-port fuel injection (SFI) engine. The main technical specifications are provided in Table 2-4.

Table 2-2. Vehicle specifications

Year/Make/Model	2022/Ford/Escape SEL Plug-in hybrid
Vehicle class (EPA)	LDT2
Odometer (miles)	3060
Engine size (L)	2.5
Fuel injection type	SFI
Max power (hp@rpm)	165@6250
Max torque (Nm@rpm)	155@4000
Air system	Naturally aspirated
Number of cylinders	4 (inline)
Engine compression ratio	13.0:1
Emissions standard	USEPA: T3B30 CA: SULEV30
Aftertreatment systems	TWC, WR-HO2S, HO2S, EGR, EGRC

2.3 Test Sequence, Randomization, and Fuel Conditioning

The vehicle was tested three times using the Federal Test Procedure (FTP) emissions test cycle and three times using US06 cycle on each fuel. The entire FTP consists of three segments, including a cold-start transient phase (0-505 s), a stabilized or hot-running phase (506-1372 s), a hot-soak phase with the engine off (9-10 min), and a hot-start transient phase (0-505 s). The FTP has a duration of 1877 s, total distance of 11.04 miles, an average speed of 21.2 mph, and a maximum speed of 56.7 mph. The FTP test cycle is shown in Figure 2-1.

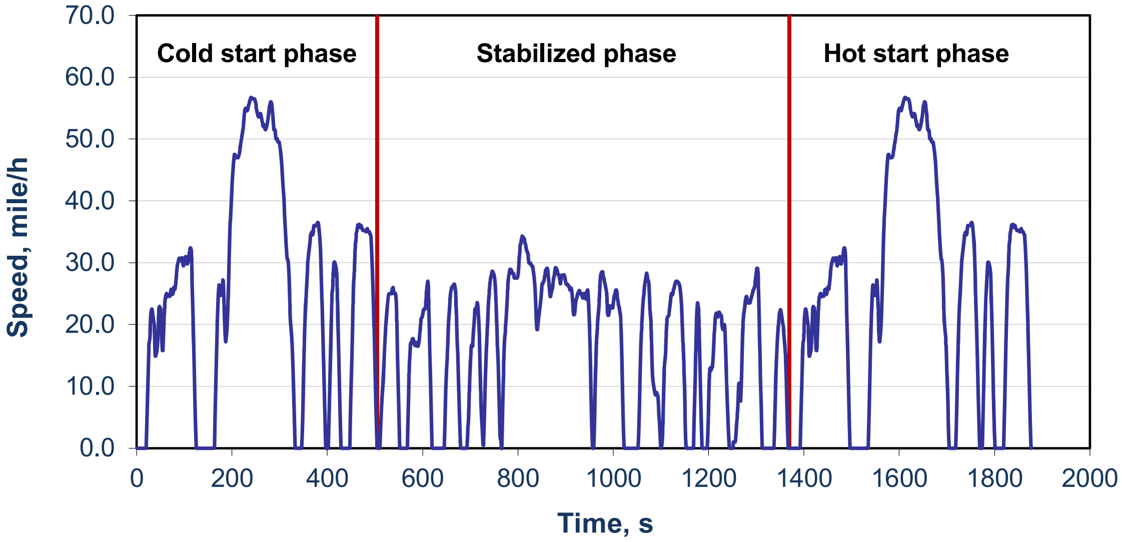

Figure 2-1. FTP cycle

The US06 Supplemental Federal Test Procedure (SFTP) was developed to address the shortcomings with the FTP-75 test cycle in the representation of aggressive, high speed and/or high acceleration driving behavior, rapid speed fluctuations, and driving behavior following startup. The cycle represents an 8.01-mile (12.8 km) route with an average speed of 48.4 miles/h (77.9 km/h), maximum speed 80.3 miles/h (129.2 km/h), and a duration of 596 seconds. The US06 test cycle is shown in Figure 2-2.

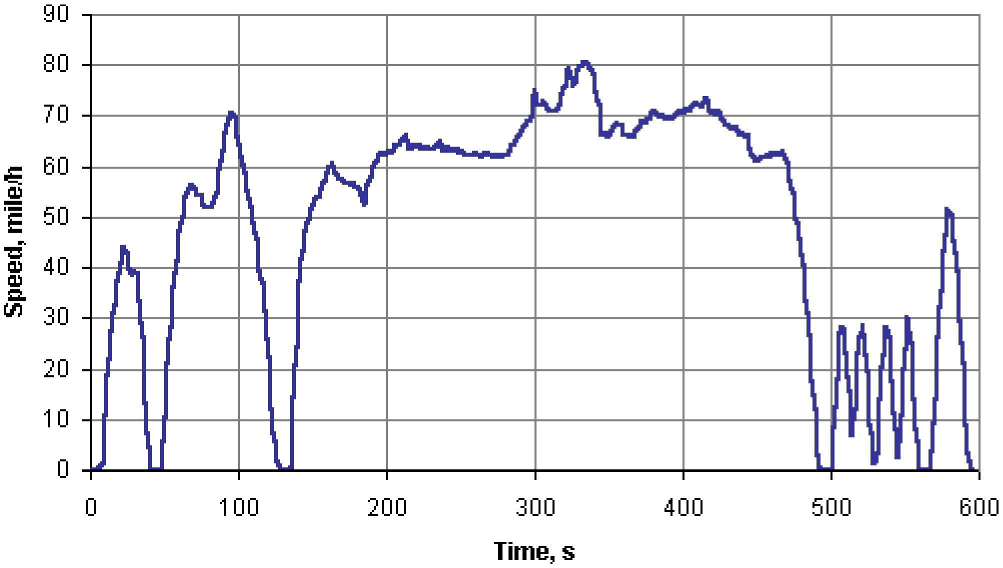

Figure 2-2. US06 cycle

2.5 Emissions Testing

Vehicle emissions measurements were conducted in CE-CERT's new state-of-the-art Light-Duty Laboratory (LDL). The centerpiece of this laboratory is a new AVL CVS AMA SL (Slim Line) system of the i60 generation using AVL's iGEM test cell automation and with an AVL dilution tunnel. The AVL CVS SL system was used to obtain standard bag measurements for THC, CO, NOx, NMHC, CH4, and CO2. The AVL CVS AMA SL system includes a flame ionization detection (FID) for THC and NMHC emissions, methane cutter (Cutter FID SL) for CH4 emissions, a chemiluminescence analyzer for NOx emissions, and a non-dispersive infrared (NDIR) analyzer for CO and CO2 emissions. All gaseous emissions were determined according to the U.S. EPA protocols for light-duty emission testing as given in the CFR, Title 40, Part 86. The LDL utilized a 48-inch Burke E. Porter single-roll electric chassis dynamometer, capable of testing vehicles weighing up to 12,000 lbs.

Fuel economy was determined using the carbon balance method, as discussed later in the report.

A schematic of the experimental setup is shown in Figure 2-3.

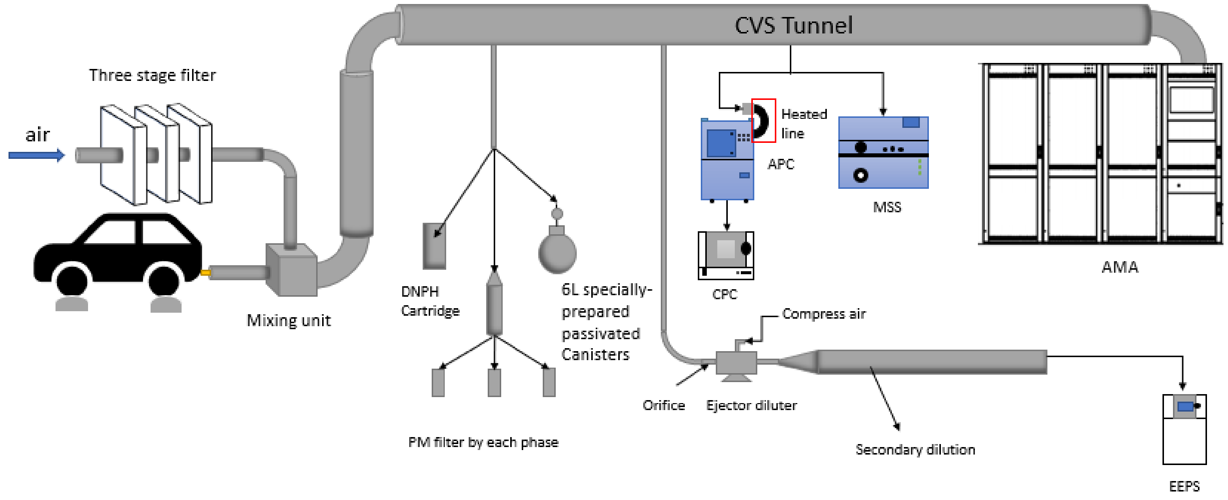

Figure 2-3. Schematic of Experimental Setup

For the FTP cycle, gravimetric PM mass samples were collected for each of the three individual phases of the FTP (i.e., cold-start, hot-running, and hot-start) and weighted PM mass over the FTP cycle were calculated based on PM mass data from each phase of the FTP. For the US06 cycle, only one filter was used to collect PM mass samples throughout the entire duration of the US06 cycle. Samples were flow-weighted based on CE-CERT's new sampling system that was built following the procedures in 40 CFR 1066 and associated references in 40 CFR Part 1065. PM samples were collected on 47 mm diameter 2 µm pore Teflon filters (Whatman brand) with flow-weighting MFCs and weighed with a 1065-compliant ultra-precision microbalance in a temperature and humidity controlled clean chamber. Buoyancy corrections for barometric pressure differences will also be made for the PM filter weights as per CFR 1065.

PM mass emissions were reported after background corrections. For this program, two (2) filter tunnel blanks were collected over the FTP and US06 cycles. The first tunnel blank was collected before the start of the testing campaign and the second was collected at the end of the testing campaign. The tunnel blank tests were performed just like regular FTP and US06 tests, except the exhaust sample line was collecting ambient air. Three filters were used to sample each phase of the FTP during the six tunnel blank tests and one filter was used to sample US06 during the two tunnel blank tests.

Carbonyl compounds (aldehydes and ketones) were measured in triplicate only for the FTP. Carbonyls were sampled on 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges (Waters Corp., Milford, MA) from the main CVS tunnel using a mass flow controller to regulate the flow to 1 L/min through the cartridge. The DNPH cartridges were eluted with 2 mL of acetonitrile and analyzed with a high-performance liquid chromatography, HPLC, (Waters 2690 Alliance System with 996 Photodiode Array Detector) following the US EPA TO-11A method. One cumulative sample was collected throughout the entire FTP cycle.

Speciated hydrocarbons were measured in triplicate only for the FTP. Hydrocarbon species were collected using a 6 L specially prepared SUMMA passivated canister, which will be connected to the CVS system. Analysis of the hydrocarbon species was conducted using a Gas Chromatography/Mass Spectrometry/Flame Ionization Detector (GC/MS/FID) analytical system according to the EPA TO-12/PAMS method and the EPA TO-15A. One cumulative sample was collected over the entire FTP cycle. Table 2-5 provides a list of species analyzed for this program.

Tunnel blanks for the carbonyl compounds and hydrocarbon species were obtained for both the FTP and US06 cycles.

Table 2-3. Hydrocarbon species analysis method

Ethylene Acetylene Ethane Propylene Propane Isobutane 1-Butene 1,3-Butadiene n-Butane trans-2-Butene cis-2-Butene Isopentane 1-Pentene n-Pentane Isoprene trans-2-Pentene cis-2-Pentene 2,2-Dimethylbutane Cyclopentane 2,3-Dimethylbutane 2-Methylpentane 3-Methylpentane	EPA TO-12/PAMS

1-Hexene n-Hexane Methylcyclopentane 2,4-Dimethylpentane Benzene Cyclohexane 2-Methylhexane 2,3-Dimethylpentane 3-Methylhexane 2,2,4-Trimethylpentane n-Heptane Methylcyclohexane 2,3,4-Trimethylpentane Toluene 2-Methylheptane 3-Methylheptane n-Octane Ethylbenzene m/p-Xylenes Styrene o-Xylene Nonane Isopropylbenzene n-Propylbenzene m-Ethyltoluene p-Ethyltoluene 1,3,5-Trimethylbenzene o-Ethyltoluene 1,2,4-Trimethylbenzene n-Decane 1,2,3-Trimethylbenzene m-Diethylbenzene p-Diethylbenzene n-Undecane n-Dodecane	
ethanol naphthalene	EPA TO-15A

3 Emissions Testing Results

This section outlines the experimental results of this program and discuss their statistical significance. Emissions of interest are NOx, CO, THC, NMHC, CH_4, CO_2, solid particle number, particle size distribution, black carbon, formaldehyde, acetaldehyde, 1,3-butadiene, benzene, toluene, ethylbenzene, m/p-xylenes, and o-xylene.

The weighted FTP and US06 emission results for the testing on the testing vehicle are presented in the figures in this section. The results for each test cycle/fuel combination represent the average of all test runs done on that combination. The error bars represent the standard deviation over the triplicate tests for each fuel. This same format is used for the figures throughout this section. The individual emissions test results for the testing vehicle are provided in Appendix A.

Statistical analysis was performed using a simple 2 tailed t-test p value for the comparison between fuels on each pollutant. For the statistical analyses, results are statistically significant for $p \leq 0.05$ or marginally statistically significant for $0.05 < p \leq 0.1$ for this discussion.

3.1 THC, NMHC and CH_4 Emissions

Figure 3-1, Figure 3-2, and Figure 3-3 show the weighted THC, NMHC, and CH_4 emissions, respectively, over the FTP cycle. THC and NMHC emissions showed strong increases with E30 and E83 fuels compared to E10. For the FTP cycle, the weighted THC emissions for E30 and E83 fuels showed a marginally statistically significant increase of 66% and a statistically significant increase of 381%, respectively, compared to E10. Similarly, the weighted NMHC emissions for E30 and E83 showed a marginally statistically significant increase of 53% and a statistically significant increase of 250%, respectively, compared to E10. CH4 emissions also showed large, statistically significant increases for E30 and E83 fuels compared to E10.

For the US06 cycle, THC and NMHC emissions were found in very low concentrations. The only statistically significant difference in NMHC emissions was seen between E10 and E83. CH_4 emissions were below the detection limits for E10 and E30 fuels over the US06.

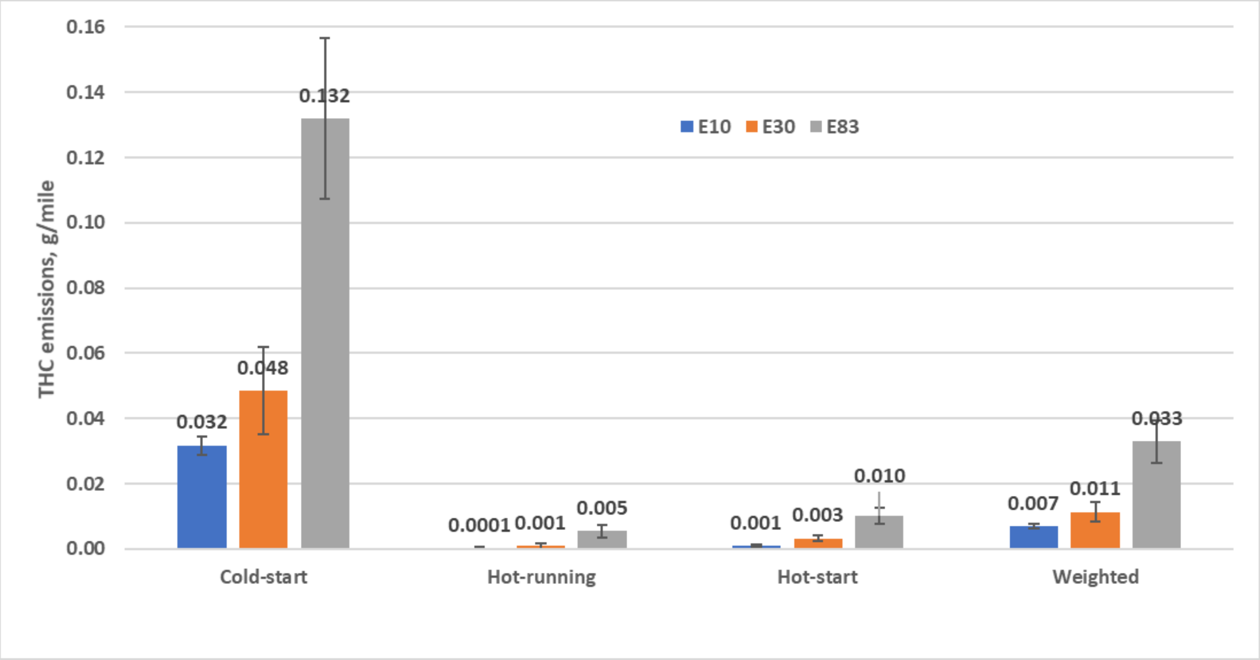

Figure 3-1. THC emissions by phase and the weighted FTP cycle

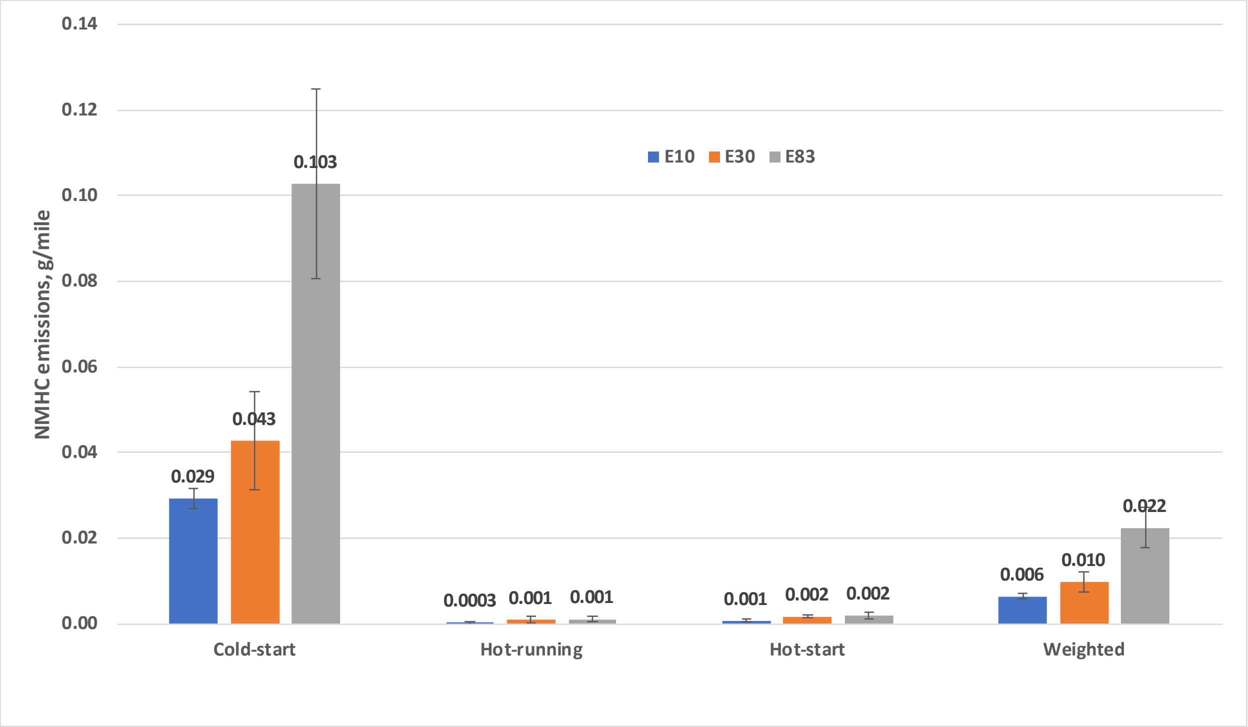

Figure 3-2. NMHC emissions by phase and the weighted FTP cycle

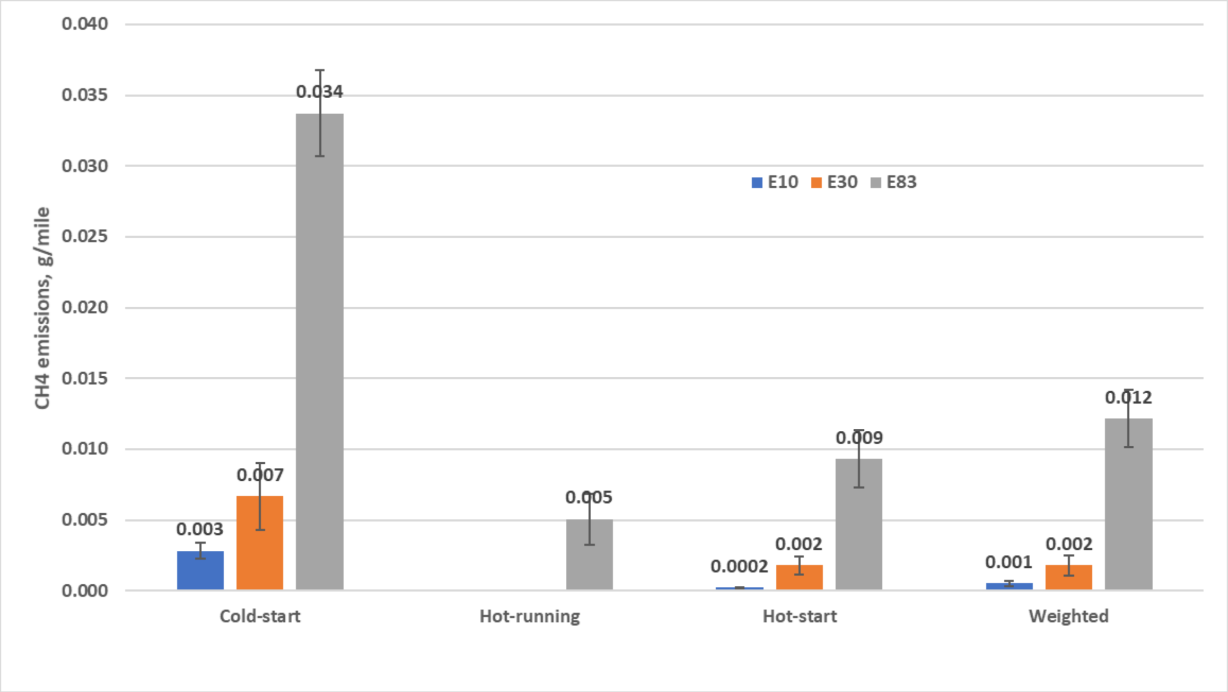

Figure 3-3. CH$_4$ emissions by phase and the weighted FTP cycle

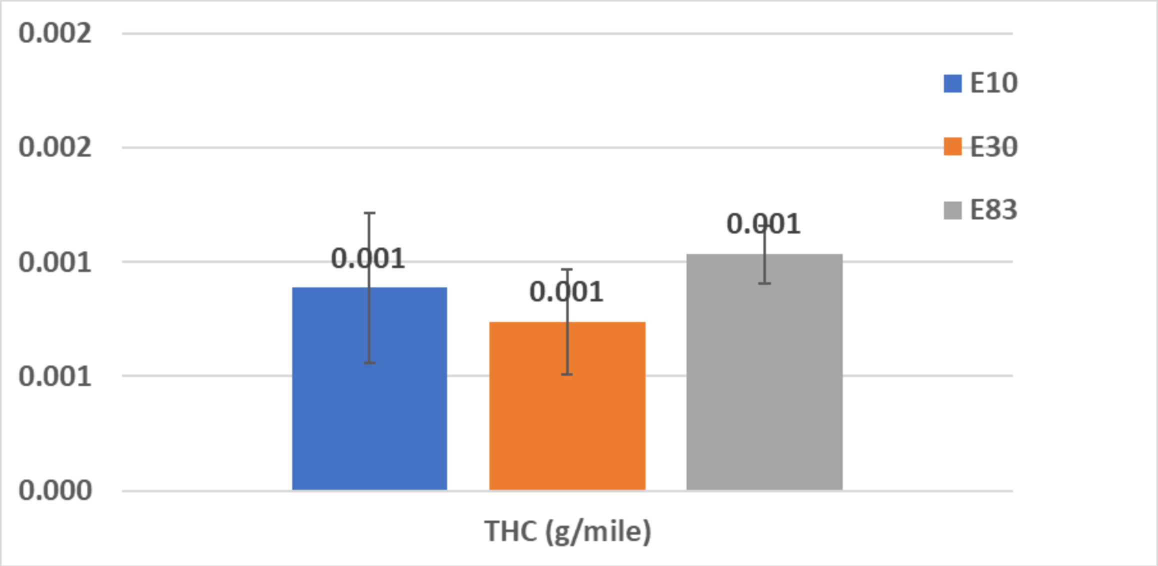

Figure 3-4. Average THC emission results for the US06 cycle

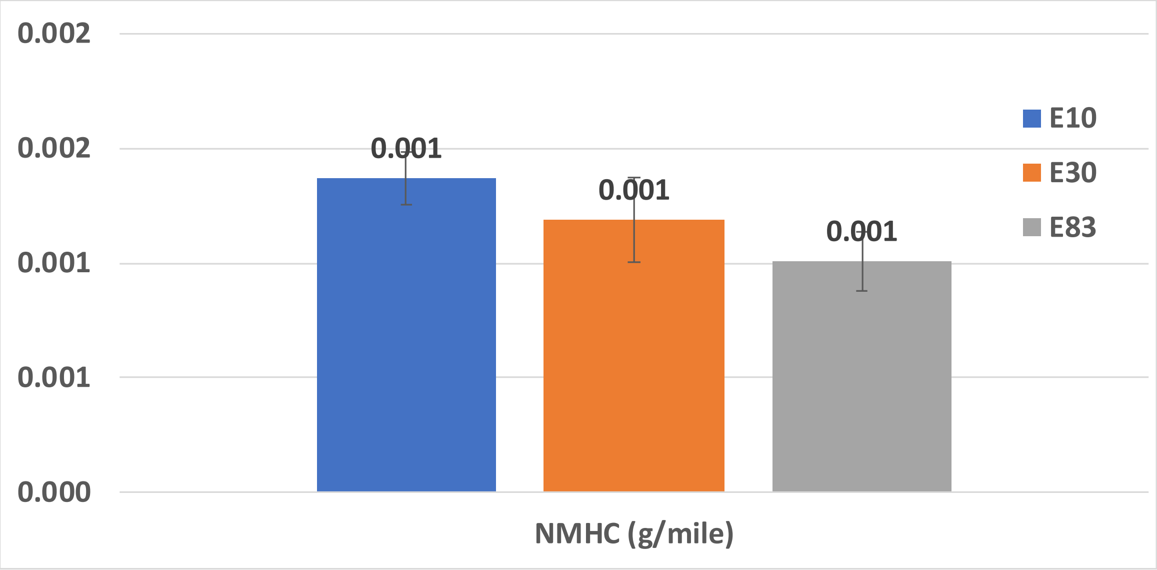

Figure 3-5. Average NMHC emission results for the US06 cycle

3.2 CO Emissions

Figure 3-6 and Figure 3-7 show the CO emissions for the FTP and US06 cycles, respectively. CO emissions with the use of E30 and E83 fuels trended higher for the FTP and US06 cycles compared to E10. However, the differences in CO emissions for both fuels were not statistically significant.

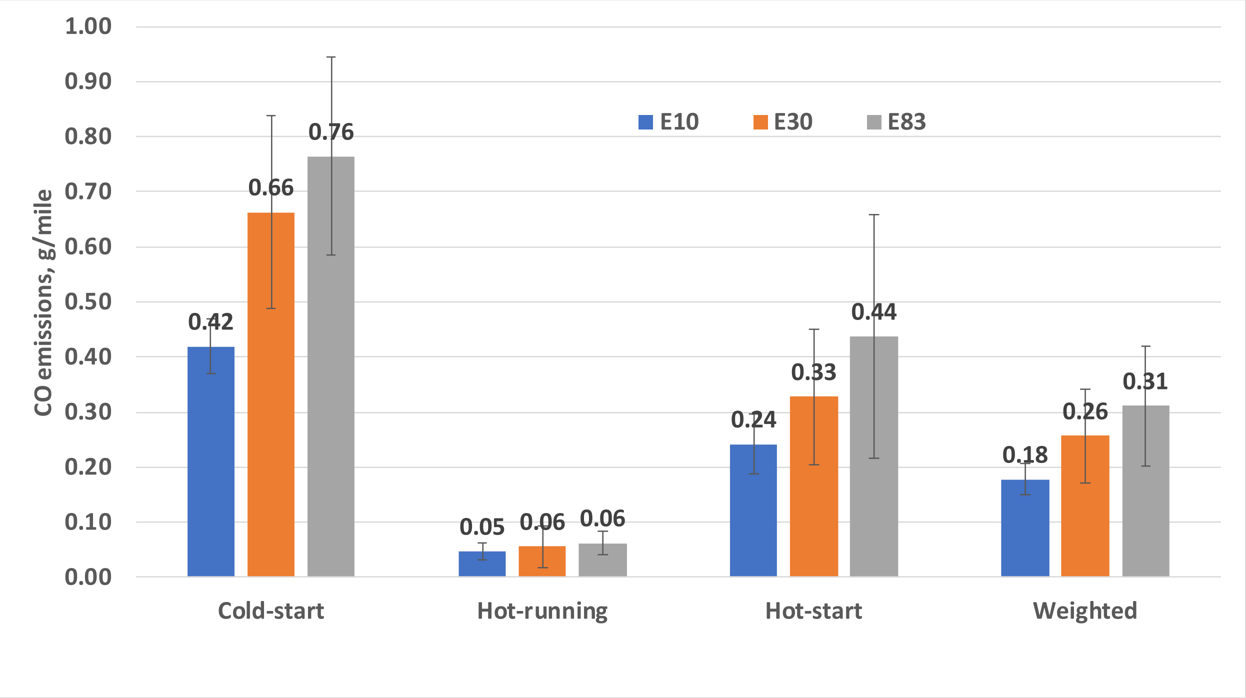

Figure 3-6. CO emissions by phase and the weighted FTP cycle

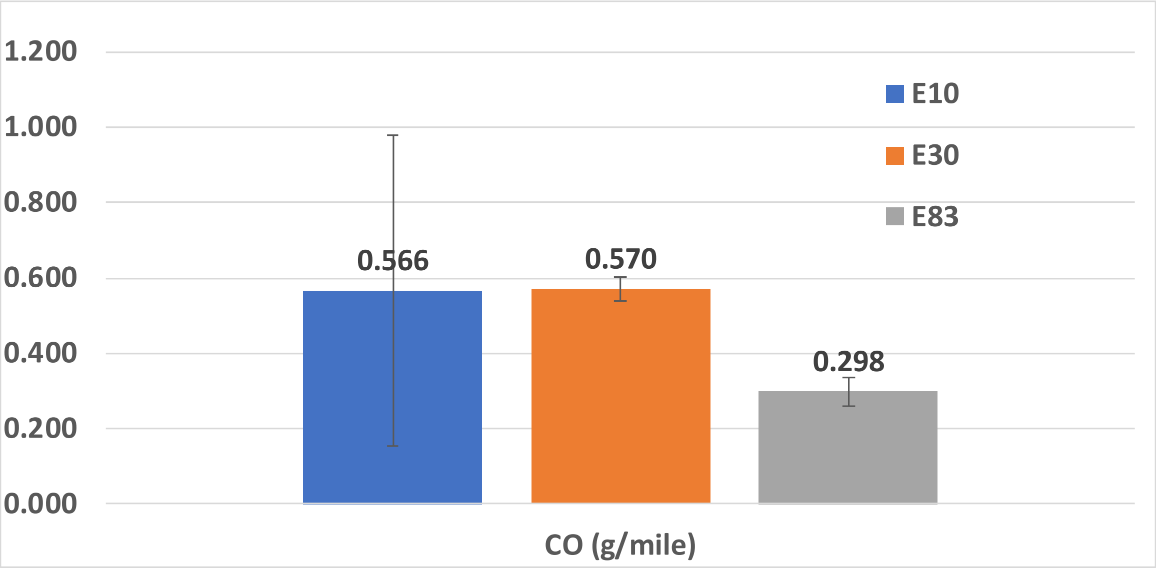

Figure 3-7. Average CO Emission results for the US06 cycle

3.3 NOx Emissions

Figure 3-8 and Figure 3-9 show the NOx emissions for the FTP and US06 cycles, respectively. For the FTP weighted NOx emissions, both E30 and E83 fuels showed reductions compared to E10. The use of E83 fuel resulted in a 48% reduction in weighted NOx emissions compared to E10, at a statistically significant level.

For the US06 NOx emissions, E83 showed a marginally statistically significant reduction of 79% compared to E10.

Our results indicate that higher ethanol blends will not adversely affect NOx emissions, but rather demonstrate strong reductions.

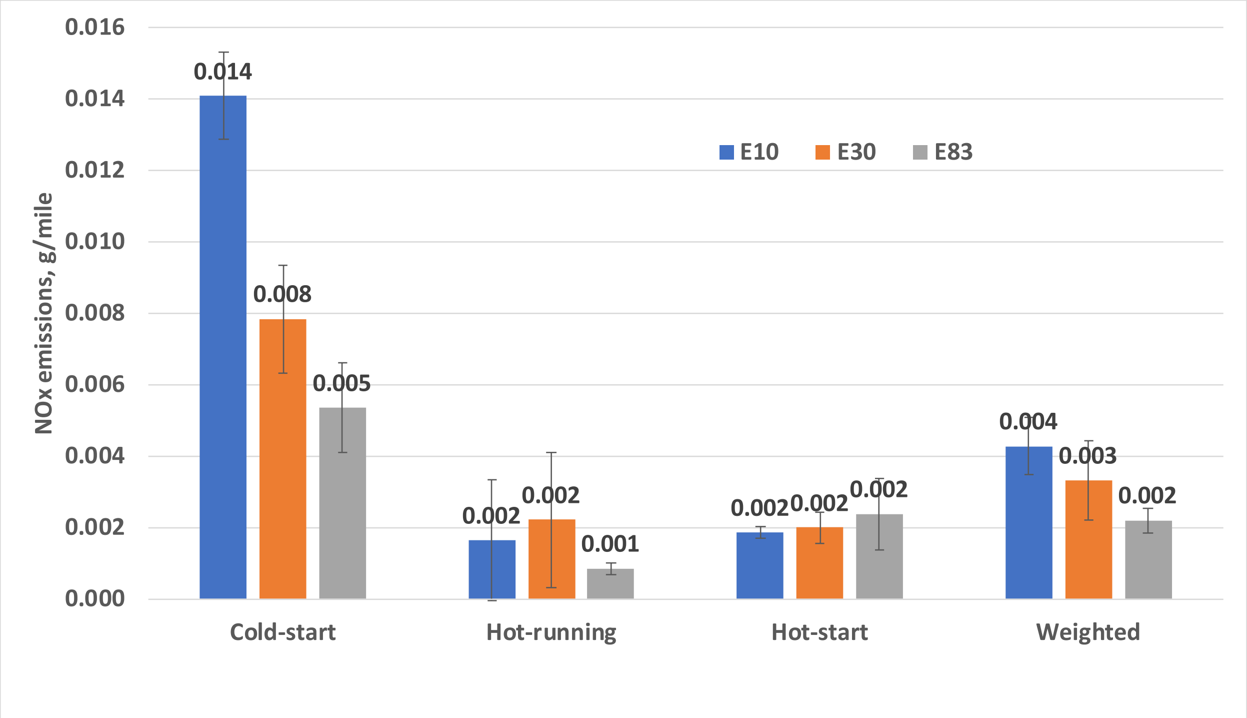

Figure 3-8. NOx emissions by phase and the weighted FTP cycle

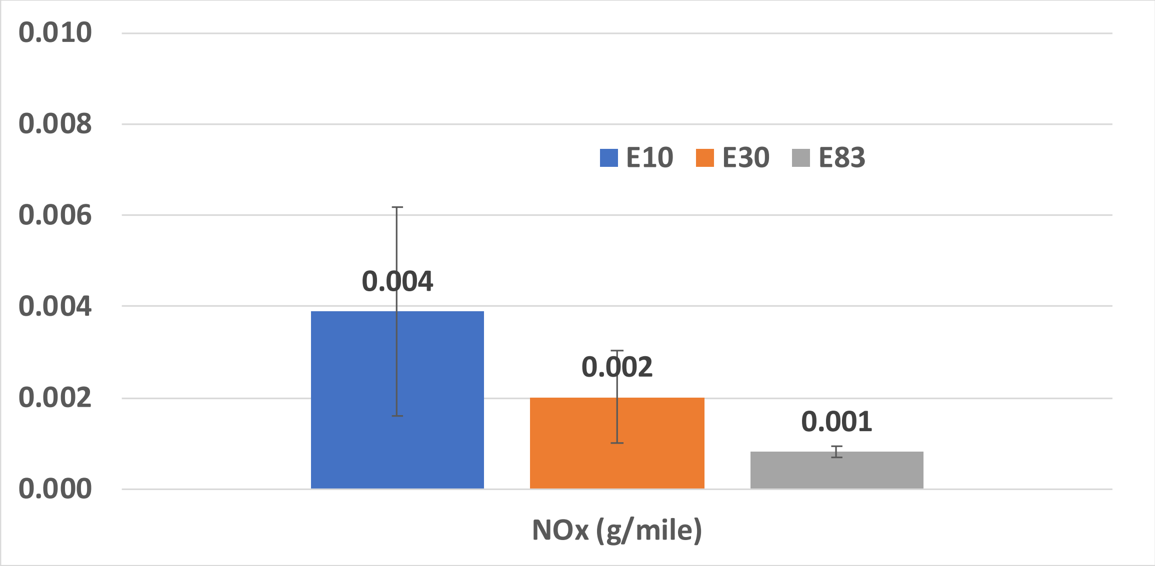

Figure 3-9. Average NOx emission results for the US06 cycle

3.4 CO_2 Emissions and Fuel Economy

Figure 3-10 and Figure 3-11 show the CO_2 emissions for the FTP and US06 cycles, respectively. CO_2 emissions trended lower for E30 and E83 than E10, but these differences were not statistically significant. For the US06 cycle, E30 and E83 trended lower for CO_2 emissions, with E83 showing a statistically significant reduction of 3% compared to the base E10.

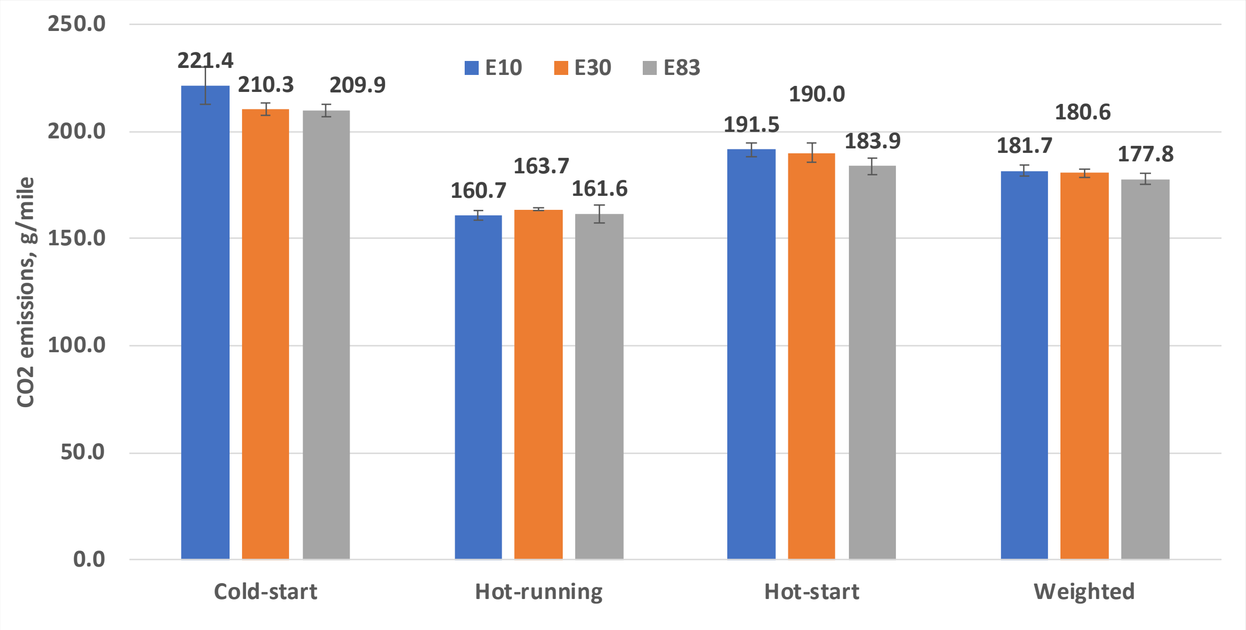

Figure 3-10. CO_2 emissions by phase and the weighted FTP cycle

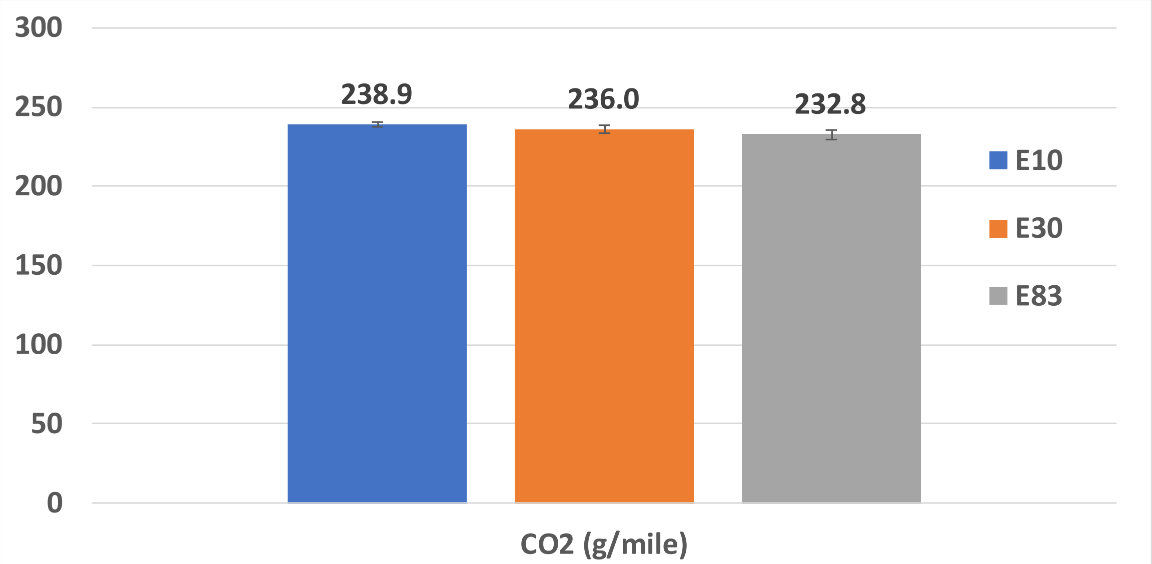

Figure 3-11. Average CO_2 emission results for the US06 cycle

Figure 3-12 and Figure 3-13 present the fuel economy results for the FTP and US06 cycles, respectively. The carbon balance method was used to calculate fuel economy. The carbon balance method provides the best comparison between the differences in energy content between different fuels. The equation used is shown below:

$$Fuel\ economy\ (mpg) = \frac{CWF_{fuel} \times SG_{fuel} \times 3781.8}{(CWF_{HC} \times HC) + (0.429 \times CO) + (0.273 \times CO_2)}$$

$HC: HC\ Emission\ Rate\ \left(\frac{g}{mile}\right)$
$CO: CO\ Emission\ Rate\ \left(\frac{g}{mile}\right)$
$CO_2 : CO_2\ Emission\ Rate\ (\frac{g}{mile})$
$CWF_{fuel}, CWF_{HC}: Carbon\ Weight\ Fraction\ of\ the\ Test\ Fuel$
$SG_{fuel}: Specific\ Gravity\ of\ the\ Test\ Fuel$

The higher ethanol blends resulted in lower fuel economy, as expected. For the FTP cycle, the weighted fuel economy had a statistically significant decrease of 7% and 26% for E30 and E83, respectively, as compared to E10. For the US06 test cycle, a similar statistically significant decrease of 6% and 25% was observed for E30 and E83 fuels, respectively, as compared to E10. The lower fuel economy for the higher ethanol blends was due to their lower energy content compared to E10.

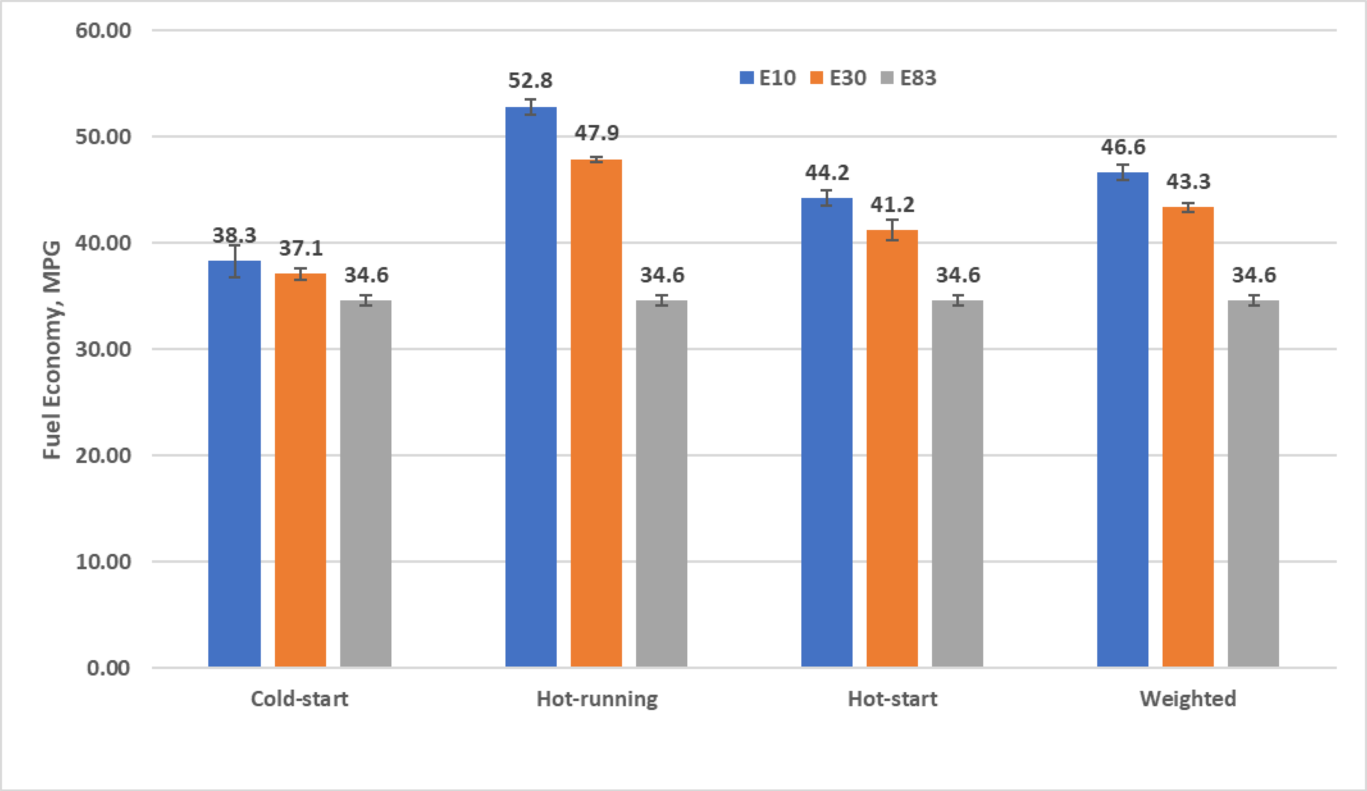

Figure 3-12. Average fuel economy results based on carbon balance for FTP cycle

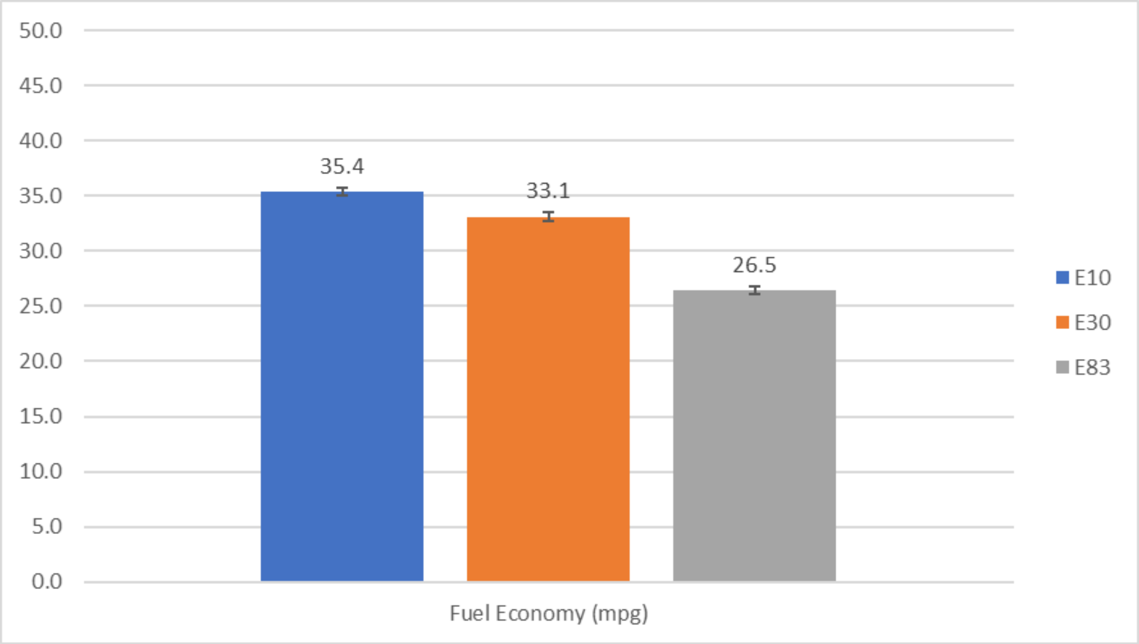

Figure 3-13. Average fuel economy results based on carbon balance for the US06 cycle

3.5 PM Mass and Solid Particle Number Emissions

Figure 3-14 and Figure 3-15 show the weighted PM mass emissions over the FTP and US06 cycles, expressed in mg/mile

For the FTP cycle, PM mass emissions were found below the optional California PM mass standard (1 mg/mile) for light-duty gasoline vehicles and trended lower with higher ethanol blending. The use of E83 showed a statistically significant reduction in the weighted PM mass emissions of 76% relative to E10.

For the US06 cycle, E30 showed a marginally statistically significant decrease in PM mass of 50% compared to E10. E83 showed a statistically significant decrease of 70% in PM mass emissions compared to E10.

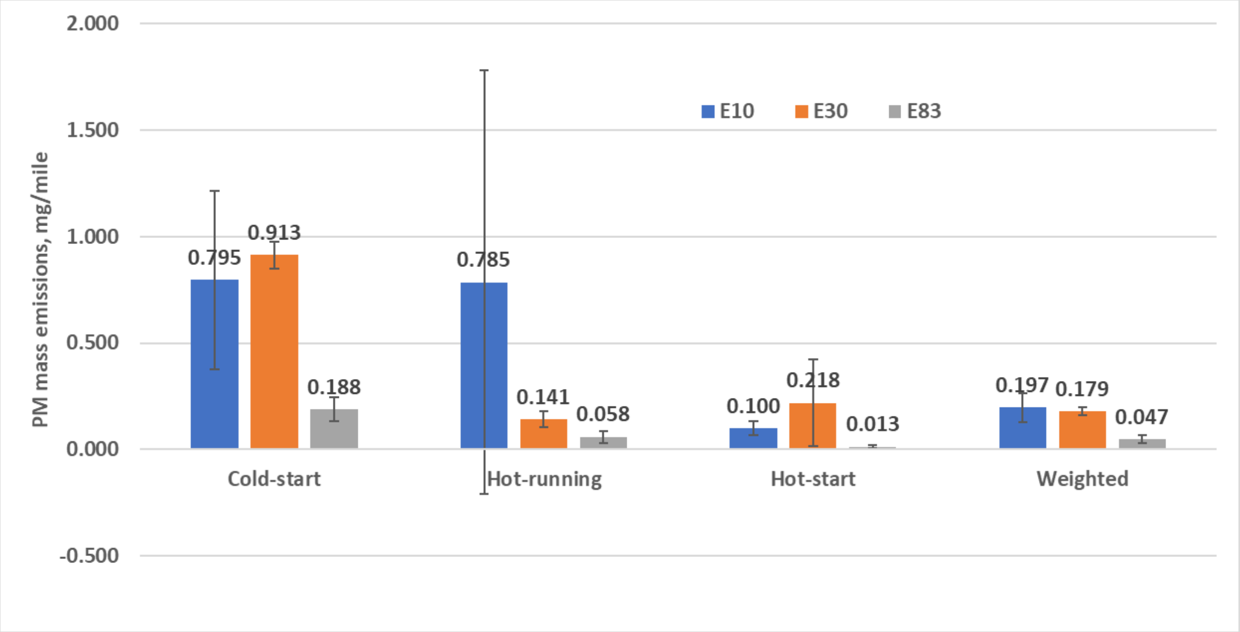

Figure 3-14. PM mass emissions for the weighted and its individual phase of the FTP cycle

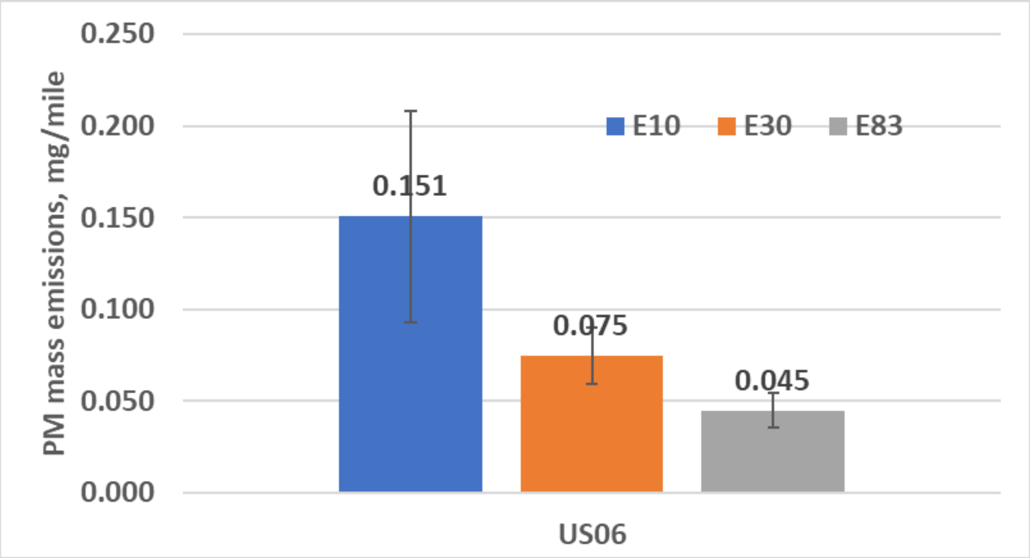

Figure 3-15. Average PM mass emissions results for the US06 cycle

Solid particle number (SPN>23 nm) emissions over the FTP and US06 cycles are shown in Figure 3-16 and Figure 3-17, respectively. For the FTP cycle, E30 and E83 trended lower for SPN>23 weighted emissions, with E30 showing a reduction of 37% compared to E10 and E83 showing a statistically significant reduction of 65% compared to E10. For the cold-start phase, SPN>23 emissions showed reductions of 41% and 74%, respectively, for E30 and E83 compared to E10. Hot-start SPN>23 emissions were 29% lower for E30, but 18% higher for E83 compared to E10. For the Hot-running phase, E30 showed reduction in SPN emissions of 27% and E83 showed marginally significant reduction of 64% compared to E10.

The cold-start period significantly contributed to the total SPN>23 emissions for all fuel combinations. Hot-running and hot-start SPN>23 emissions were significantly lower than the cold-start phase.

For the US06 cycle, E30 and E83 showed decreases in SPN emissions of 73% and 16%, respectively, compared to E10.

The reduction of aromatic hydrocarbons via dilution effects and the presence of oxygen were the main contributing factors for the reductions in PM mass and SPN emissions with E10 and E83 fuels.

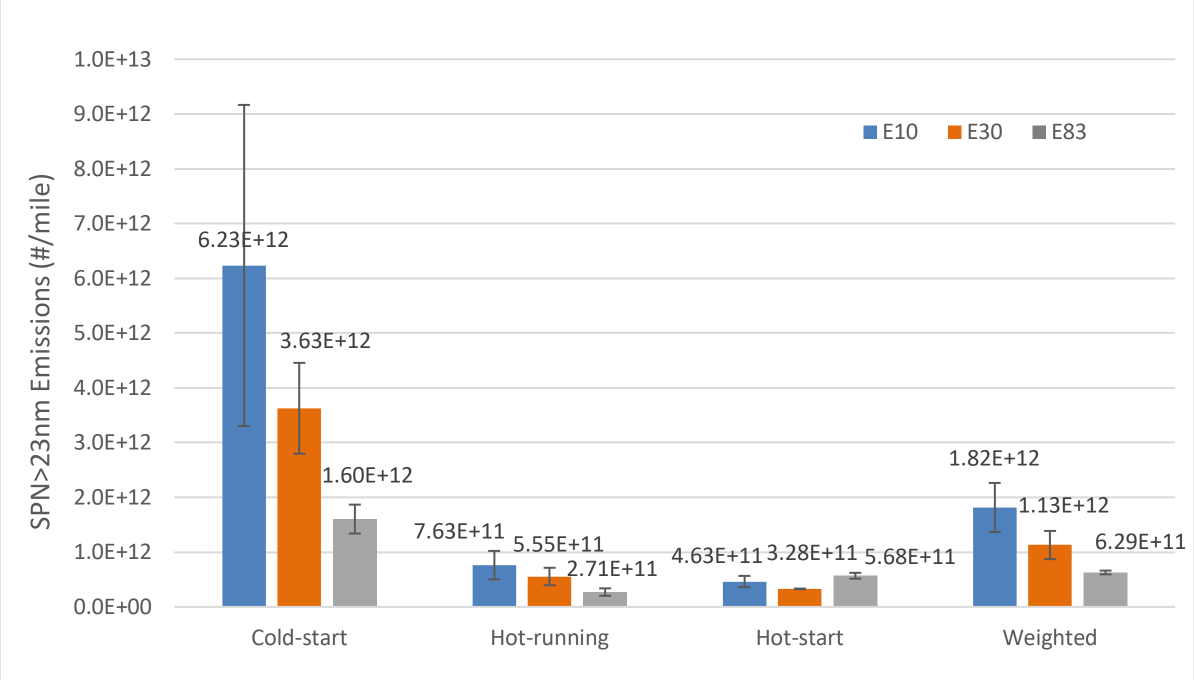

Figure 3-16. Solid Particle Number (>23 nm) Emissions for the weighted and its individual phase of the FTP cycle

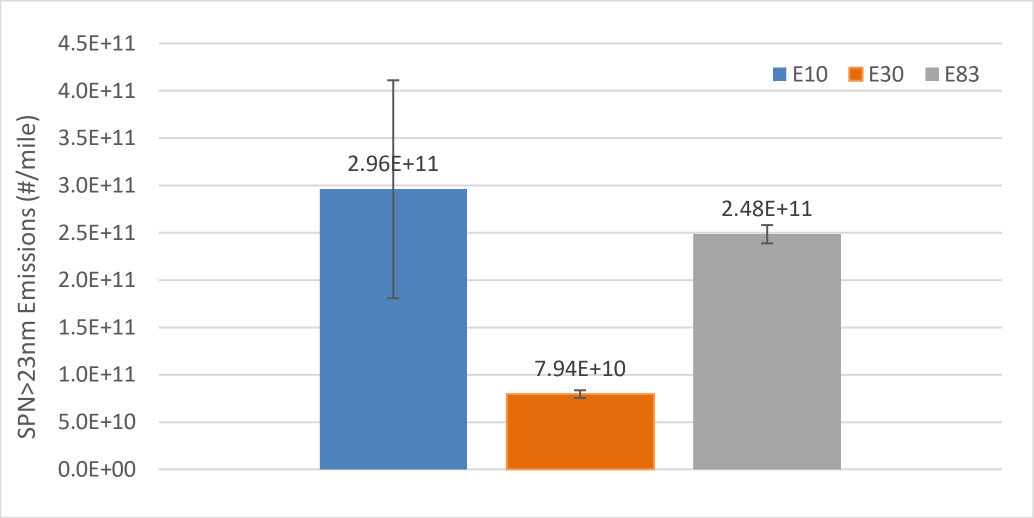

Figure 3-17. Average Solid Particle Number (>23 nm) Weighted Emissions Results for US06 cycle